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D. M. Williams
D. P. Kuban

Oak Ridge National Laboratory[b]
Oak Ridge, Tennessee 37831
615/574-6387

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TRACTION-DRIVE FORCE TRANSMISSION FOR TELEROBOTIC JOINTS*

D. P. Kuban and D. M. Williams

Oak Ridge National Laboratory
Oak R·dge, Tennessee 37831-6353

Abstract

The U.S. Space Station Program is providing many technological developments to meet the increasing demands of designing such a facility. One of the key areas of research is that of telerobotics for space station assembly and maintenance. Initial implementation will be teleoperated, but long-term plans call for autonomous robotics. One of the essential components for making this transition successful is the manipulator joint mechanism.

Historically, teleoperated manipulators and industrial robotics have had very different mechanisms for force transmission. This is because the design objectives are almost mutually exclusive. A teleoperator must have very low friction and inertia to minimize operator fatigue; backlash and stiffness are of secondary concern. A robot, however, must have minimum backlash, and high stiffness for accurate and rapid positioning. A joint mechanism has yet to be developed that can optimize these divergent performance objectives.

A joint mechanism that approaches this optimal performance was developed for NASA Langley, Automation Technology Branch. It is a traction-drive differential that uses variable preload mechanisms. The differential provides compact, dexterous motion range with a torque density similar to geared systems. The traction drive offers high stiffness and zero backlash - for good robotic performance, and the variable-loading mechanism (VLM) minimizes the drive-train friction - for improved teleoperation. As a result, this combination provides a mechanism to allow advanced manipulation with either teleoperated control or autonomous robotic operation. This paper will address the design principles of both of these major components of the joint mechanism. Various materials were evaluated for the traction rollers, and two were tested. Also, various surface modifications to these rollers were studied utilizing previous NASA Lewis experience. Both modified and unmodified materials were tested. For the VLM, several designs were investigated to determine the trade-offs between friction and compliance, as well as the effects of dimensional tolerances and structural deflection. Various designs were fabricated and tested. Test results from the test joints are included. Also, the preliminary results of the complete master/slave assembly are discussed. At the time of this writing, final assembly is under way. Finally, the paper describes some of the limitations of this mechanism, as well as recommendations for further development of this technology.

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1. Introduction

The purpose of developing a telerobotic work package for space application is to increase astronaut and overall system safety, productivity, and flexibility. Astronaut safety is of increasing concern because of the number of potentially hazardous tasks, such as hydrazine fuel transfer, being planned for space execution. Astronaut risks increase as the demand for extra vehicular activity (EVA) time (as much as 2000 h per year has been projected) increases for work on large projects such as space station assembly, operation, and maintenance activities. A remote system would allow around-the-clock operation while the astronaut-operators remain safely inside the orbiter or space station. Finally, with a telerobotic-based dexterous remote-handling system, operations can be conducted at significant distances (such as geosynchronous orbit) from the orbiter or space station.

The basic criteria for this telerobotic work package are very straightforward. First, the criteria must replace the dexterity of a suited astronaut, while allowing the operator to work remotely in a "shirt-sleeves" environment. In addition, the design must allow for the transition from near-term teleoperation to far-term autonomous robotic operation.

Traditionally, teleoperated manipulators have been designed primarily to operate with low friction and inertia to minimize operator fatigue and backlash and stiffness were of secondary concern. Robots, on the other hand, are designed with high stiffness and minimum backlash as a primary concern to accommodate accurate and rapid positioning; friction and inertia are addressed secondarily, if at all. The design objectives of teleoperators and robots dictate mechanical approaches that are almost mutually exclusive. Attempts to merge these technologies into a "telerobot" have been strictly limited by these contradictory approaches. To accomplish this merger, a joint mechanism is needed that provides very low friction and inertia to accommodate teleoperator requirements and high stiffness and zero backlash to accommodate robotic requirements. A joint mechanism has yet to be developed that can optimize both of these requirements. However, a joint mechanism that approaches this optimal performance has been developed for NASA Langley, Automation Technology Branch. It consists of a traction drive differential that uses variable-loading mechanisms (VLM) and is called the Laboratory Telerobotic Manipulator (LTM).

2. Traction-Drive Joint Mechanism for the LTM

The LTM is a seven-degree-of-freedom telerobot that employs replicated traction drive joint mechanisms as shoulder, elbow, and wrist joints (Fig. 1). Each joint mechanism provides pitch and yaw motions about orthogonal axes. Each joint is attached to the adjacent joints by means of only four fasteners to produce a modular mounting arrangement that allows the LTM arms to be easily assembled and disassembled. This modularity also allows the LTM arms to be easily reconfigured for changing requirements and permits maintenance on the arms by simple module replacement.

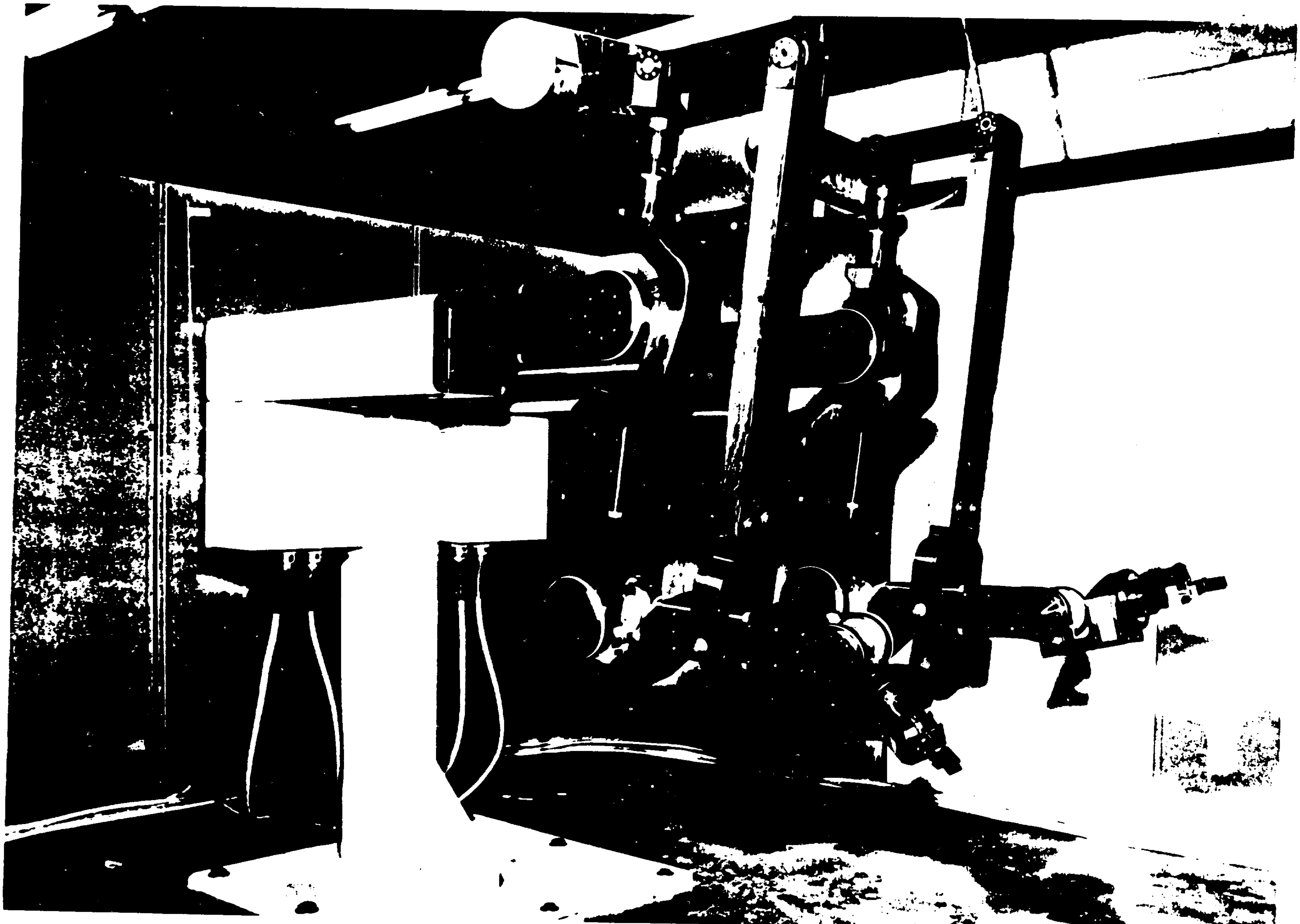

Fig. 1. Laboratory Telerobotic Manipulator (LTM) Slave

The LTM has load capacities to accommodate man-equivalent operation. Each LTM arm has a peak load capacity of 30 lb and a continuous load capacity of 20 lb. To accomplish this requirement effectively, the LTM arm was configured by joints having different torque capacities. The resulting torque requirement for each joint is 435 in.-lbs for the wrist, 960 in.-lbs for the elbow, and 1650 in.-lbs for the shoulder. To reduce the fabrication and engineering cost, a large joint having a peak torque capacity of 1650 in.-lbs is used at both shoulder and elbow positions. In an effort to optimize dexterity and minimize weight, a small joint having a peak torque capacity of 435 in.-lbs is used as the wrist joint. An assembly of the small joint is illustrated in Fig. 2. The large joint is simply an enlarged replica of the small joint and is illustrated in Fig. 3. Both joint assemblies consist of a differential drive mechanism, two DC servomotors (Inertial Motors) with gearheads, two torque sensors, and two resolvers as shown in Figs. 2 and 3. The speed-reduction ratio through the differential is 3-1/2 to 1. Special gearhead (Bayside Controls) with spring-loaded antibacklash gear trains were used. Commercially available (GSE) torque sensors have been modified and incorporated directly into the joint mechanism to produce a compact arrangement. Vernitron resolvers are located at each joint axis and are coupled directly to the axis of rotation. These resolvers and torque sensors provide the control system data indicating the joint's payload and position.

Cabling provisions have also been made to eliminate the use of external pigtails and connectors. A through-passage within the differential has been provided to accommodate the cabling bundle. This cabling bundle is also equipped with electrical connectors positioned at each mounting interface that engage and disengage automatically as each joint is attached and detached to the adjacent joint.

Permanent-magnet fail-safe brakes have recently become commercially available (Electroid) and have been coaxially mounted to each drive motor. These brakes will safely stop each LTM arm during power failure and will provide the capability of supporting maximum payloads for long periods without motor overheating. The operating principle of a permanent-magnet brake is similar to that of a standard spring-set brake in the sense that permanent magnets are used to generate a magnetic force that replaces the spring force of the spring-set-type brakes. When the coil of a permanent magnet brake is energized, it cancels this magnetic force, releasing the clamping force on the drive disc. The real advantage of these brakes is the amount of torque per unit size and weight. These magnetic units are capable of supplying five times the torque-to-weight ratio as spring-set brakes.

The differential drive mechanism has two inputs and one output which rotate about orthogonal axes. Force transmission through the differential drive mechanism is accomplished by traction drives. Unlike force transfer through gear teeth that generate torsional oscillation as the load transfers between teeth, force transfer through traction is inherently smooth and steady, without backlash, and relatively stiff.[1] The elements of this traction differential drive can be seen in Fig. 4. Two driving rollers provide input into the differential. A significant advantage in this setup is that each driving roller is required to transmit only one-half of the

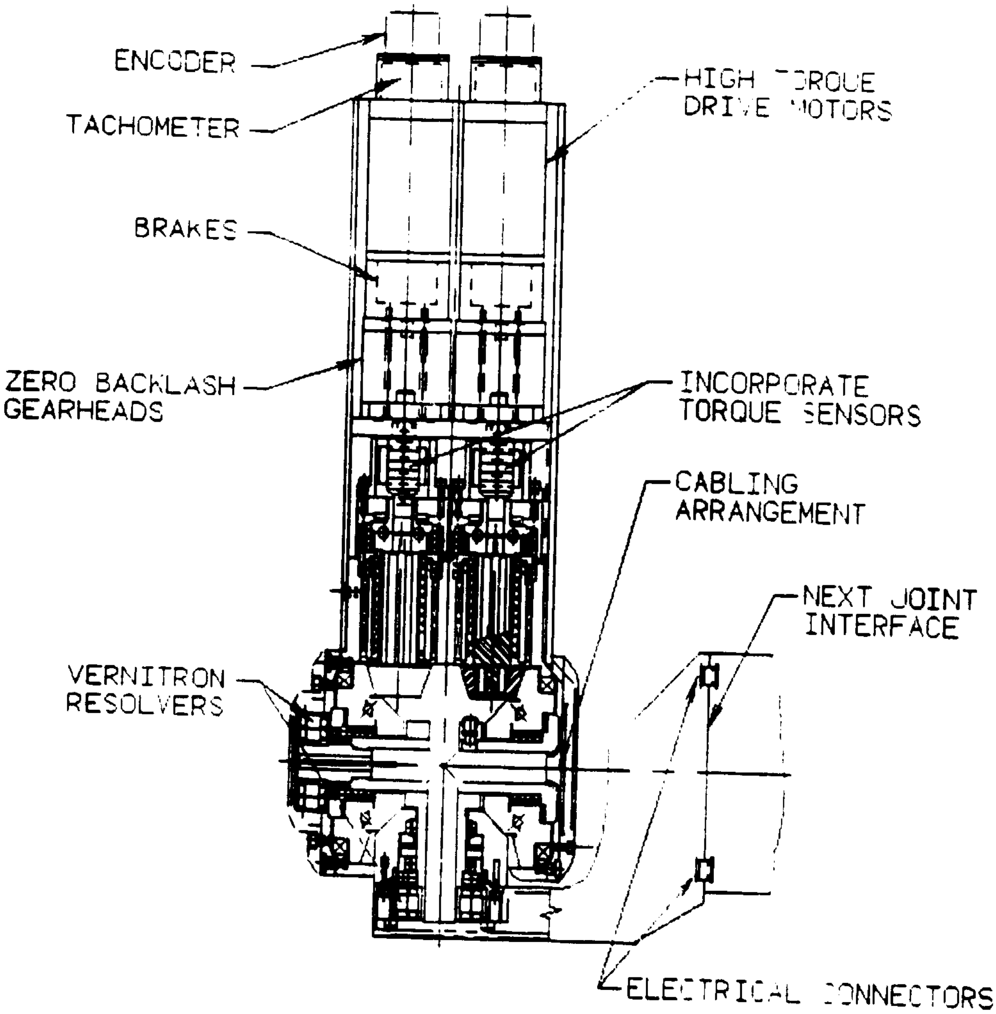

Fig. 2. LTM small pitch/yaw joint assembly.

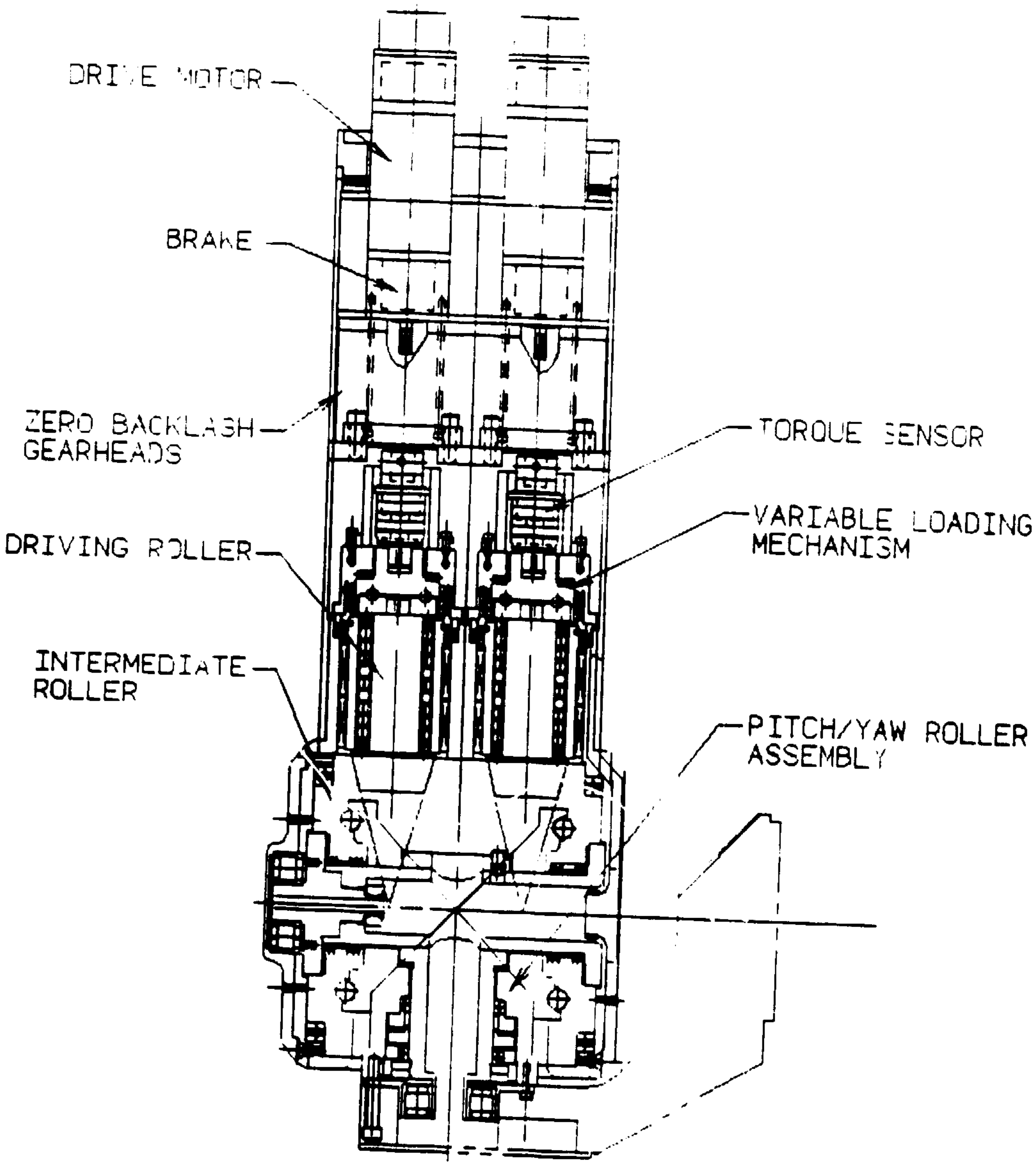

Fig. 3. LTM large pitch/yaw joint assembly.

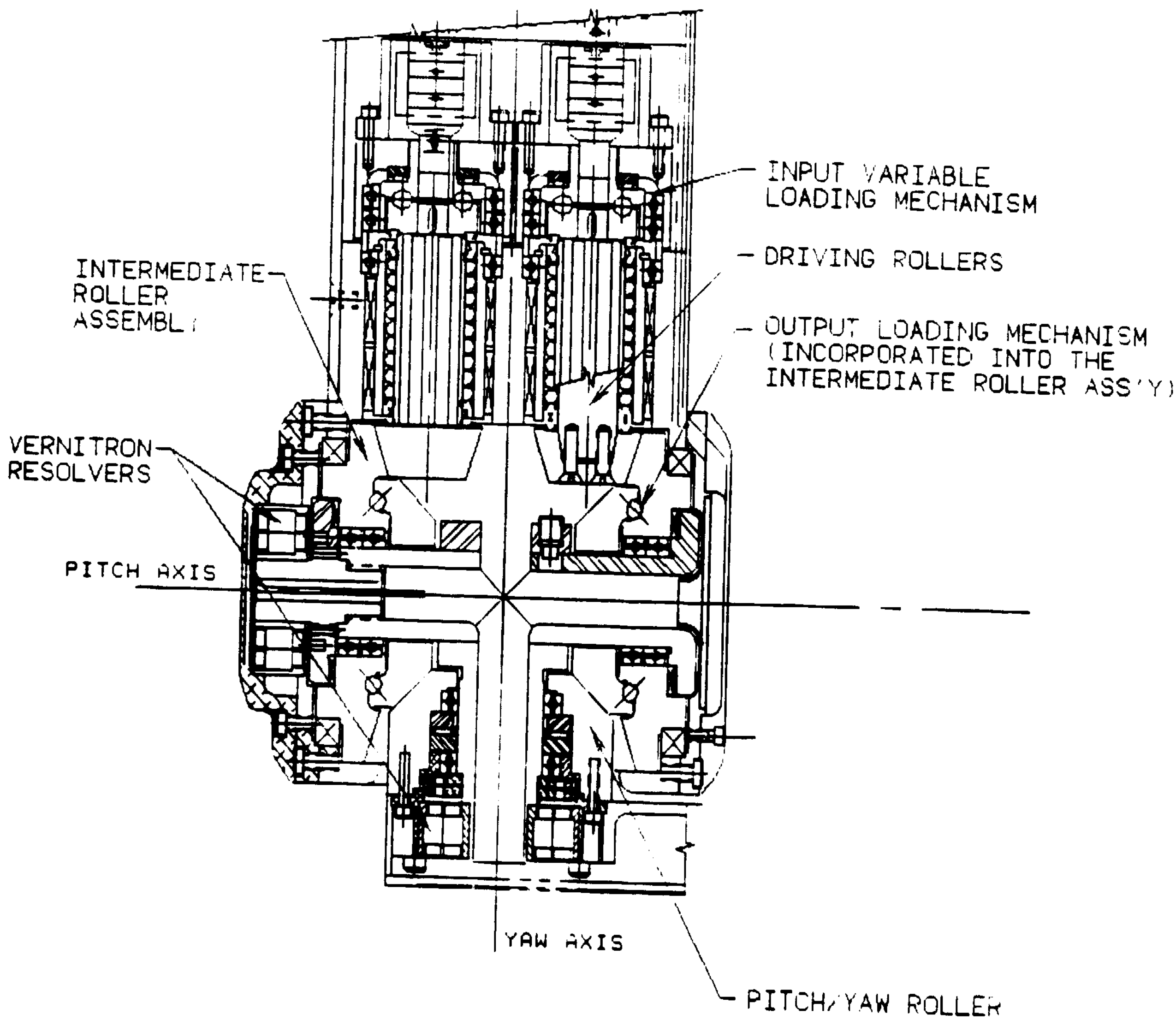

Fig. 4. LTM traction drive differential.

total torque necessary to make a particular motion. These rollers drive two intermediate roller assemblies, which in turn drive the pitch/yaw roller about the pitch and yaw axes. The axis about which the pitch/yaw roller rotates depends on the direction of rotation of the driving rollers. The pitch/yaw roller is driven about the pitch axis when the driving rollers rotate in opposite direction. When both driving rollers are rotated in the same direction, the pitch/yaw roller is driven about the yaw axis. The rolling surfaces of the differential are gold plated in an ion-plating process developed by NASA Lewis Research Center.[2] This plating serves as a dry lubricant in the sense that it prevents the substrates from contacting. Vernitron resolvers are located at each joint axis in an effort to maximize positioning accuracy. By locating these resolvers directly at each joint axis, any creep events that occur through the traction drive differential will not effect the positioning characteristics of the LTM.

VLMs have also been employed as an alternative to constant-loading mechanisms in an effort to improve the differentials back-driveability, mechanical efficiency, and fatigue life. Constant-loading mechanisms produce a constant normal load between the traction drive rollers. This constant normal load must be sized to ensure adequate traction at the joints maximum torque capacity. The obvious disadvantage of this constant normal load is that the traction drive rollers and their supporting bearings are needlessly overloaded during periods of low torque transmission. This constant normal load not only generates extra bearing losses at low torque transmission but, more important, shortens the drive systems fatigue life.[3] To ensure adequate traction with minimum friction loss, VLMs were developed. These mechanisms produce varying normal loads between the traction rollers that are proportional to the transmitted torque.[4] Two VLMs variable loading mechanisms have been incorporated into the traction drive differential. These VLMs are known as the input VLM and the output VLM.

The input VLM produces a varying normal load between the input roller and the intermediate roller assembly. This mechanism consists of a upper thrust cam, a lower thrust cam, a thrust bearing, two radial bearings, a thrust bearing retainer, and four ball bearing balls, referred to as cam balls as shown in Fig. 5. This mechanism generates a thrust force proportional to the input torque. This thrust force is applied to the input roller and is counteracted by the thrust bearing and bearing retainer. The radial bearings provide stability to the upper thrust cam. The upper and lower thrust cams are equipped with tapered contours that are formed by helical grooves. These contours contain cam balls as illustrated in Fig. 6. Each contour is formed by two helical grooves, one cut on a right-hand helix and the other cut on a left-hand helix. These two helical grooves converge at a depth that is slightly less than that of the cam ball radius (0.031 in). A free-body diagram cf the upper thrust cam and lower thrust cam is shown in Fig. 7. The input torque (T_i) is transmitted from the upper thrust cam to the lower thrust cam by a compressive force generated in each cam ball. This compressive force F is normal to the tangent helical groove and is the resultant force of a horizontal force F_T and a vertical force F_L. Force F_T is the tangential

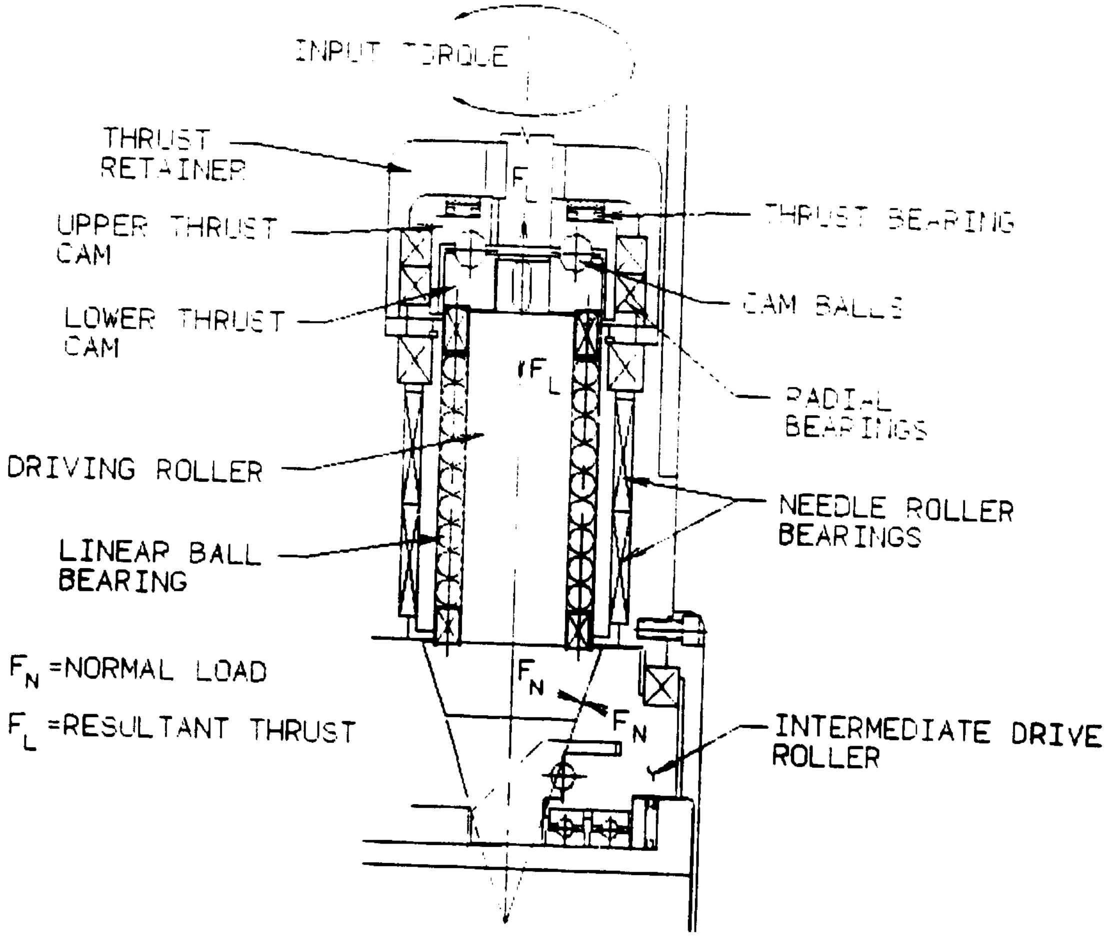

Fig. 5. Input variable-loading mechanism.

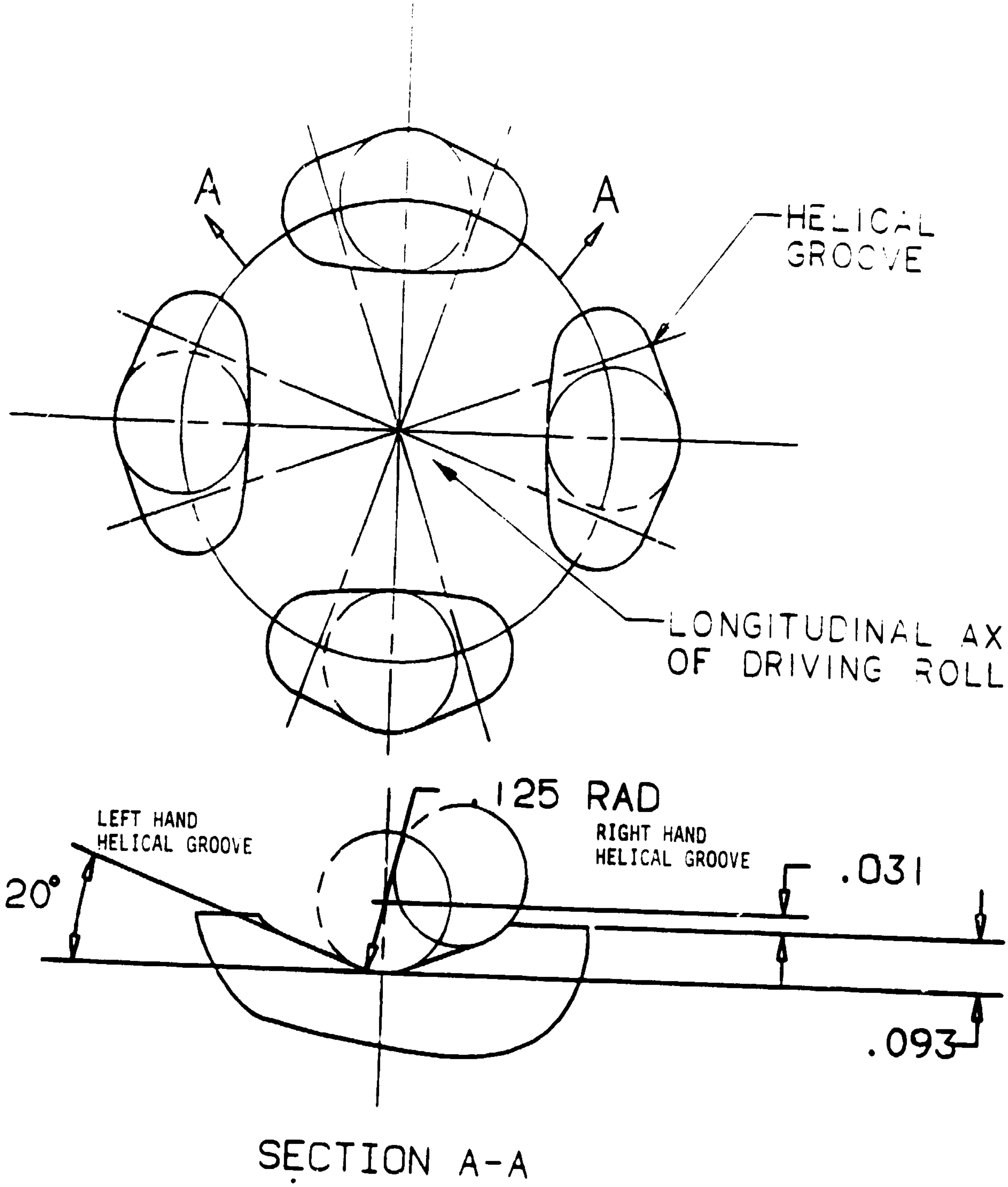

Fig. 6. Thrust cam groove detail.

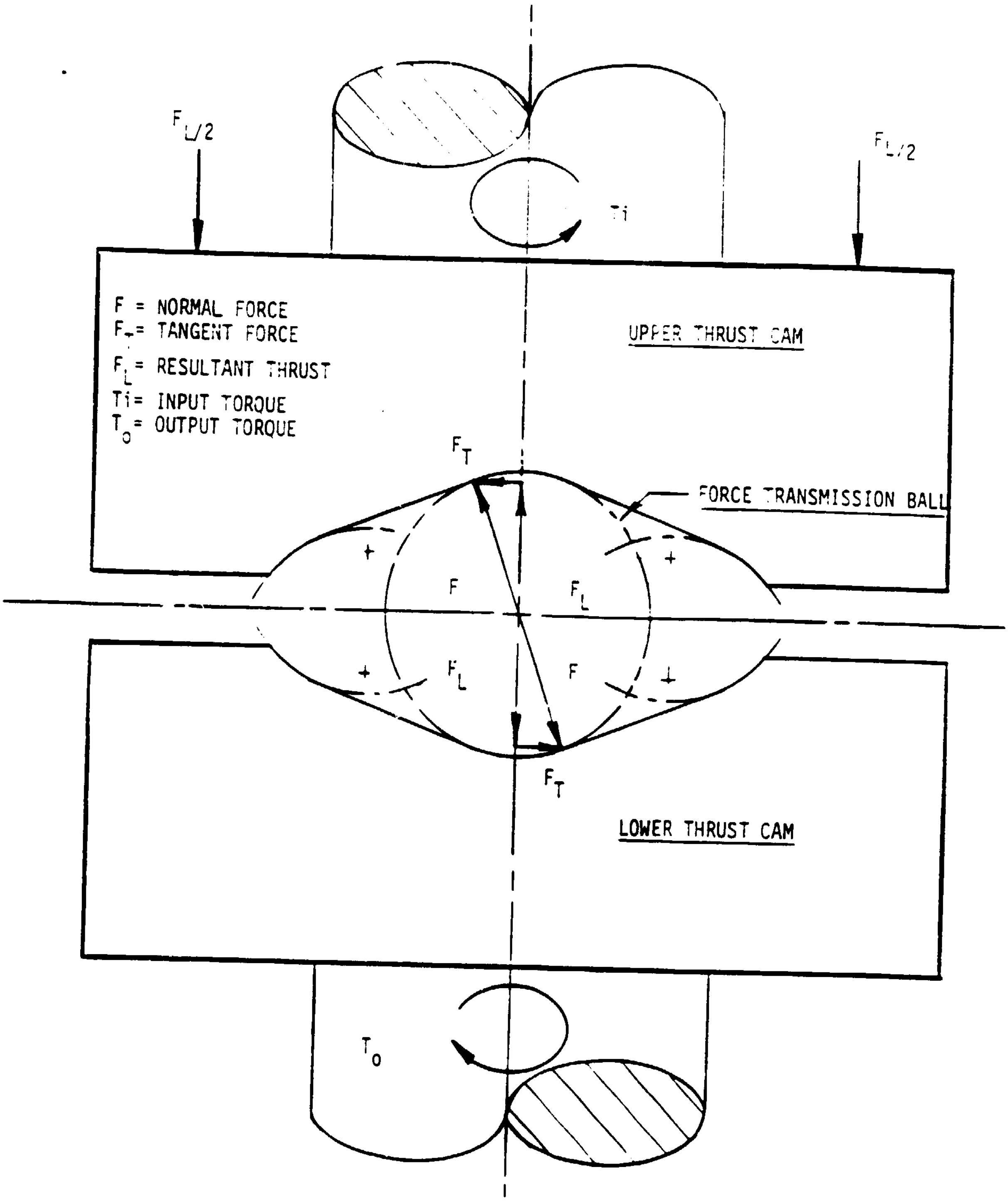

Fig. 7. Free-body diagram of variable loading mechanism.

force required to transmit the input torque T_i. Force F_L is a varying thrust load that is counteracted by the thrust bearing and bearing retainer shown in Fig. 5. This varying thrust load is applied to the input roller and produces a varying normal load between the input roller and intermediate roller assembly.

The output VLM produces a varying normal load between the intermediate roller assembly and the pitch/yaw roller. This mechanism is incorporated into the intermediate roller assembly as shown in Fig. 6. It consists of the intermediate drive roller, eight cam balls, and an intermediate transversing roller. These rollers contain tapered contours that work in conjunction with the cam balls in the same manner as the upper and lower thrust cams of the input VLM. As torque is transmitted between the intermediate drive roller and intermediate transversing roller a thrust force F_L is generated that produces the varying normal force F_N.

The operational performance of the LTM was verified through testing during its preliminary design. A photograph of the test stand used is shown by Fig. 8. The test stand was originally designed to accommodate two different types of speed reducers; a power hinge reducer, which was seen to be economically unfeasible; and a harmonic drive reducer, which is now being used. The test-stand differential is very similar to the LTM small-joint differential. Similar bearings and traction drive rollers are employed in both cases. The test stand is equipped with an input VLM and an output constant-loading mechanism. This arrangement provides the capability to compare the two different types of loading devices. Some of the parameters tested were the starting torque, back-driveability, mechanical efficiency, and torque capacity. The test stand demonstrated that a traction drive differential equipped with VLMs will satisfactorily transmit its designed torque capacity with a mechanical efficiency of 90%. Testing also indicated that a VLM generates only 25% of the starting and back-driving torques, whereas the constant-loading mechanism generated 75% of these differential torques. This appears to indicate that the VLM may reduce the starting and backdriving torque to 50%.

3. Conclusions

A joint mechanism for a space telerobot was developed for NASA Langley Research Center. This joint mechanism incorporates a traction-drive differential that is equipped with variable preload mechanisms. It meets the requirements of both teleoperators and robots. Backlash is eliminated and high stiffness is provided that accommodates accurate and rapid positioning needed in robots; and low friction and inertia is obtained to minimize operator fatigue needed in teleoperated manipulators. By meeting the requirements of teleoperated manipulators and robots, this joint mechanism is the first operational system to mechanically merge these two technologies into a "telerobot".

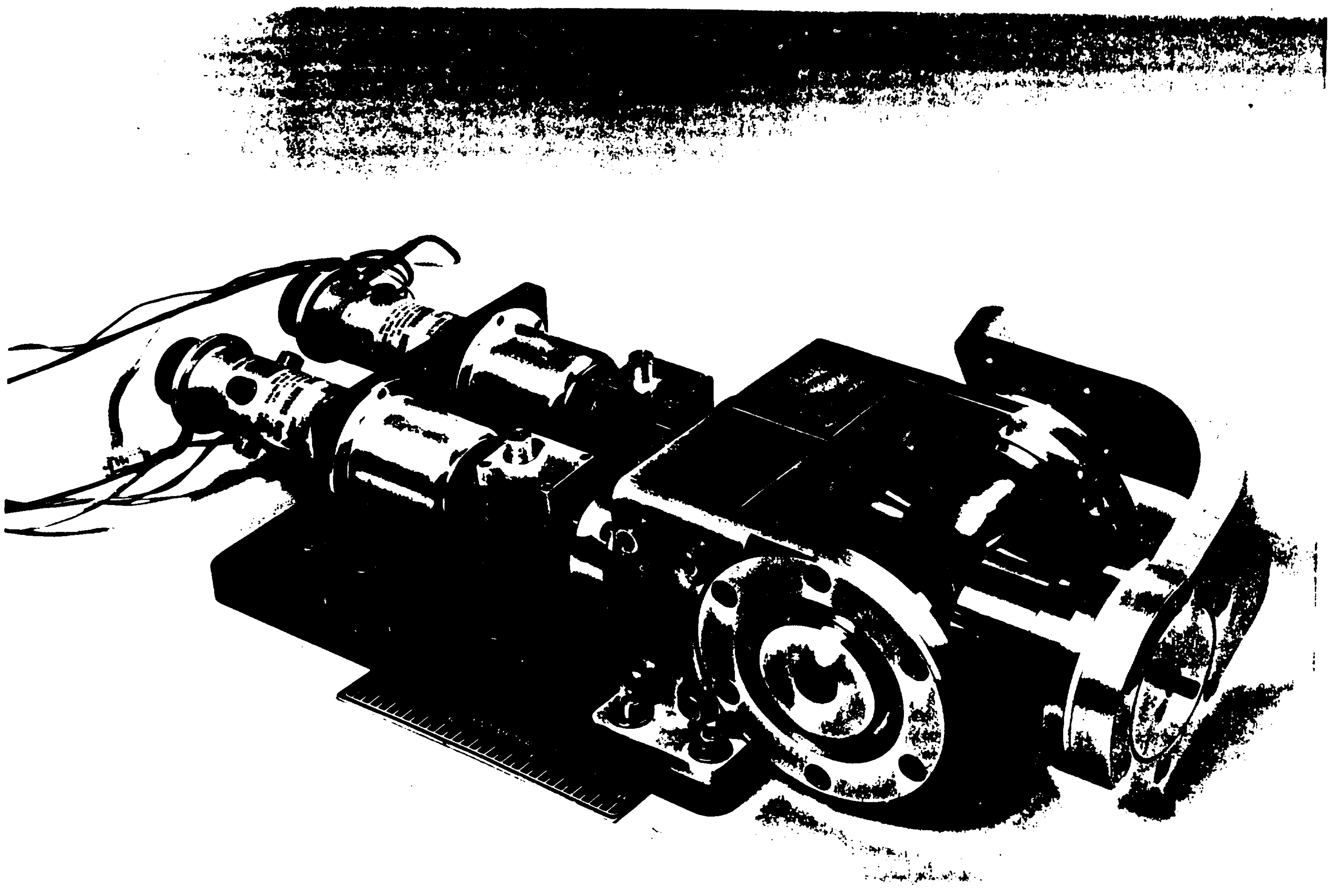

Fig. 8 LTM test stand

4. References

1. Stuart H. Loewenthal, Douglas A. Rohn, and Bruce M. Steinetz, "Applications of Traction Drives as Servomechanisms," presented at the 19th Aerospace Mechanism Symposium.

2. William Anderson, Bruce M. Steinetz, and Douglas A. Rohn, "Evaluation of a High-Torque Backlash-Free Roller Actuator," presented at the 20th Aerospace Mechanism Symposium.

3. Rothbart, ed. Mechanical Design and Systems Handbook - 1985, Loewenthal, Zaretsky, Traction Drives, Chap. 34, 1985.

4. Stuart H. Loewenthal and Erwin V. Zaretsky, "Design of Traction Drives," NASA Reference Publication 1154, 1985.